EXHIBIT D

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U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

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PUERTO RICO DEPARTMENT OF NATURAL AND ENVIRONMENTAL RESOURCES

SCIENTIFIC INVESTIGATIONS MAP 3092
Groundwater-Quality Survey of the South Coast Aquifer of Puerto Rico, April 2 through May 30, 2007
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Introduction

The increased potential for variability of groundwater quality in the South Coast aquifer of Puerto Rico due to saline water encroachment from the Caribbean Sea and from deep parts of the aquifer has become a major concern of water planners and managers. In an effort to determine the extent and sources of this encroachment, the U.S. Geological Survey (USGS) and the Puerto Rico Department of Natural and Environmental Resources conducted a synoptic groundwater-quality survey from April 2 through May 30, 2007, for the South Coast aquifer between Ponce and Arroyo (fig. 1). Groundwater resources in this aquifer extend 150 square miles in south-central Puerto Rico and provide an estimated 44.2 million gallons per day (Mgal/d) or about 61 percent of the total water needs. This amount includes: 15.3 Mgal/d for irrigation, 27.4 Mgal/d for public supply, and 1.5 Mgal/d for industrial and other uses (W.L. Molina-Rivera, U.S. Geological Survey, written commun., 2007). Since 1980 when most of the south coastal plain was intensively cultivated for sugarcane, total groundwater withdrawals have declined about 32 Mgal/d with the greatest decline occurring in irrigation (37.2 Mgal/d) and the greatest increase occurring in public supply (5.5 Mgal/d). Although withdrawals have declined substantially, a major concern is that aquifer recharge provided by irrigation return flow from surface-water irrigation canals has essentially dropped to zero because of the large-scale implementation of groundwater drip irrigation systems.

Purpose and Scope

The purpose of this report is to present the assessment of groundwater-quality data obtained during the synoptic survey conducted April 2 through May 30, 2007, that can be used by water-resource managers and planners to gain a better understanding of aquifer conditions. The data consist of in-situ measurements at active wells or piezometers for specific conductance, pH, temperature and acid neutralizing capacity (ANC, formerly referred to as alkalinity, ANC is now used exclusively for filtered water samples) and water sample collection and preparation for laboratory analyses of common dissolved constituents (ANC, calcium, magnesium, sodium, potassium, sulfate, fluoride, silica) and trace constituents (boron, iron, and manganese). These data were used to define the regional distribution of dissolved solids concentration and major hydrochemical facies in the aquifer. The data were also compared to historical data collected at several sites in the study area.

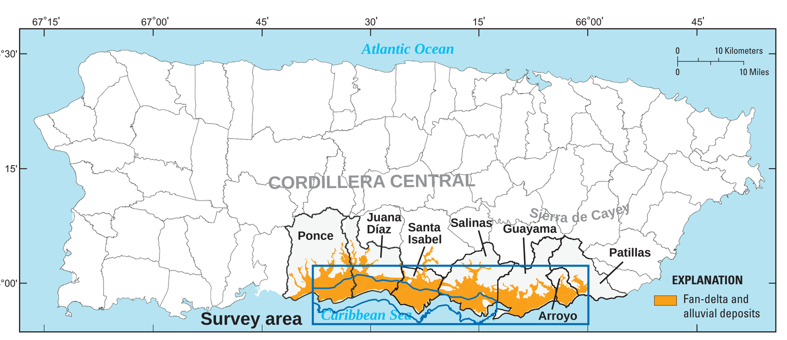

Figure 1. Location of survey area.

Hydrogeologic Setting

The survey area in Puerto Rico is between Ponce and Arroyo and is bound to the north by the foothills of the Cordillera Central and the Sierra de Cayey Mountains, to the south by the Caribbean Sea, to the west by the Río Portugués, and to the east by the Río Patillas (fig. 1 and 2). The major geologic units in the survey area are also presented on figure 2. Groundwater occurs primarily in Quaternary surficial deposits that include fan delta and alluvial sediments. These deposits are typically less than 100 feet thick in areas east of the Río Jueyes, but could be as much as 1,000 feet thick near the coast in areas to the west of the Río Jueyes (Renken and others, 2002). The surficial deposits between the Río Portugués at Ponce and the Río Coamo are underlain by carbonate units of Tertiary age with permeable limestone units that are hydraulically connected with the surficial deposits, thus both hydrogeologic units are considered as one aquifer unit in this area. The basal part of the aquifer in the Río Portugués to Río Coamo area consists of claystone strata of the underlying Juana Díaz Formation (fig. 2). Volcanic rocks of Tertiary and Cretaceous age form the base of the aquifer east of Santa Isabel.

Methods and Techniques

Groundwater samples were collected once from 50 active wells that include: 23 wells for irrigation use, 19 wells for public-supply use, 5 wells for industrial use, and 3 wells for domestic use. In addition, 11 piezometers were pumped using a 0.75 horsepower submersible pump to collect samples representative of groundwater at the respective well-screen interval open to the aquifer. Water samples were collected during April and May 2007, a period of stable hydrologic conditions at the end of the relatively dry season along the south coast. Field measurements were obtained and water samples for laboratory analyses were collected and preserved according to USGS protocols (U.S. Geological Survey, variously dated). Water samples were analyzed at the USGS National Water Quality Laboratory in Denver, Colorado. The analytical results were used to develop a map showing the distribution of dissolved solids in the aquifer consisting of the sum of the concentration of cations (calcium, magnesium, sodium, and potassium), anions (sulfate and fluoride), silica, and carbonate. Specific conductance measurements and their conversion to dissolved solids concentration values at selected surface-water sites are included in figure 3 to present the effects of streams on dissolved solids concentrations in the aquifer.

Hydrochemical facies were used to delineate aquifer areas as to the prevailing water type using the trilinear diagram method (Piper, 1944). Predominant end-member hydrochemical facies in the survey area are: sodium bicarbonate [$NaHCO_3$], sodium chloride [$NaCl$], calcium bicarbonate [$Ca(HCO_3)_2$], and calcium chloride [$CaCl_2$]. The $NaHCO_3$ results from the weathering of plagioclase minerals present in the volcanic rocks along the northern perimeter of most of the coastal plain and in areas where the volcanic rocks form the base of the aquifer. The NaCl results from seawater encroachment along the coast and $Ca(HCO_3)_2$ from freshwater infiltration through soils and surficial deposits. The $CaCl_2$ results from groundwater in the limestone rocks that lie along the perimeter of the aquifer or at depth, especially in the western half of the coastal plain. This residual sodium chloride in the rock matrix and from aquifer areas contains a mix of freshwater and seawater. Hydrochemical facies for inland parts of the survey area were delineated using water-quality information from USGS databases. Because the effect of saline intrusion is nonexistent in the inland parts of the survey area, hydrochemical facies are expected to be influenced by the composition of the aquifer matrix.

In addition to the use of major ions to define the hydrochemical facies, the chloride-to-bromide mass ratio was used as an indicator of freshwater and seawater mixing. The chloride-to-bromide mass ratio has been successfully used to study the origin of saline groundwater and brines from relatively deep geologic formations and to characterize atmospheric precipitation, shallow groundwater, and domestic sewage (Davis and others, 1998; Panno and others, 2006).

Dissolved Solids and Hydrochemical Facies

Groundwater sample collection sites are shown on figure 2. Numbers identifying sample collection sites in figure 2 correspond to well map numbers shown in table 1, which presents the analytical results of the collected samples. Figure 3 shows the distribution of dissolved solids in the South Coast aquifer for conditions during April–May 2007. Six values from samples collected during 2002 in the Ponce area (Rodríguez and others, 2005) were added to figure 3 to delineate the dissolved solids concentration contours. Dissolved solids concentrations are lowest in the area east of the Río Jueyes in the eastern part of the coastal plain. In this part, dense and relatively impermeable volcanic rocks border the aquifer along the north or form its base. Low dissolved solids concentrations occur near stream courses and are indicative of streamflow infiltration to the aquifer. To the west of the Río Jueyes, limestone rocks border the aquifer along the north and extend beneath the surficial deposits. The limestone is moderately permeable and, unlike the volcanic rocks, is subject to dissolution by groundwater flow that increases the concentration of calcium and bicarbonate. In areas where the limestone is constituted by the mudstone unit of the Juana Díaz Formation, the limestone can also contribute sodium, chloride, and sulfate from halite and anhydrite that are present in small quantities in the rock matrix (Glover, 1971). Throughout the entire aquifer, dissolved solids concentrations increase toward the coast. The sources of these increases may be natural causes such as upwelling of mineralized deep groundwater to coastal discharge areas, evapotranspiration of groundwater, infiltration of seawater during high sea level stages, and the effects of sea aerosols near the coast. Artificial causes that could contribute to an increase in dissolved solids concentrations are upconing of more mineralized groundwater by overexploitation of the aquifer, dewatering works, and inland movement of the freshwater-saltwater interface from a reduction of groundwater flow toward the coast. The analytical results from sampled wells and piezometers given in table 1 were used to prepare the trilinear diagrams presented in figures 4*A* through 4*F*. The areal distribution of hydrochemical facies in the aquifer are shown in figure 5.

A more thorough discussion of the areal variation of dissolved solids concentrations and hydrochemical facies is presented by subareas due to the heterogeneous nature of aquifer hydrologic and hydrogeologic conditions. The subareas with relatively similar aquifer hydrologic and hydrogeologic conditions are west of the Río Jacaguas, the Río Jacaguas to the Río Descalabrado, the Río Descalabrado to the Río Jueyes, the Río Jueyes to the Río Seco, and east of the Río Seco. Historical data from different wells collected during 1960 through 1965 and from 1986 through 1987 were used to compare changes in hydrochemical facies.

West of the Río Jacaguas

Dissolved solids concentrations in this area ranged from 324 to 5,860 mg/L (fig. 3). Dissolved solids in well 5 had increased by 338 mg/L from 1965 to 2007, and the chemical characteristics indicate a trend of increasing sodium and chloride concentrations (fig. 4*A*). Water-quality data from well 6 showed a trend towards the calcium-chloride water type (fig. 4*A*) and a decrease in dissolved solids concentration of 61 mg/L from 1986 (Gómez-Gómez, 1991) to 2007. The principal hydrochemical facies west of the Río Jacaguas is the calcium-chloride water type (figs. 4*A* and 5). This water type is associated with the mixture of saline and freshwater, and with geochemical facies of the Juana Díaz Formation (Rodríguez and others, 2005). Results from water samples collected at well 3 indicate a water type of sodium-chloride (fig. 4*A*), which is an indicator of saline water intrusion (Rodríguez and others, 2005).

The Río Jacaguas to the Río Descalabrado

Dissolved solids concentrations ranged from 330 to 472 mg/L (fig. 3). The lower dissolved solid concentrations to the east of the Río Jacaguas are indicative of streamflow infiltration into the aquifer. Historical groundwater-quality data (Gómez-Gómez, 1991) indicated no change in water type (calcium-bicarbonate) in well 14 (fig. 4*B*) and a dissolved solids concentration decrease of 22 mg/L from 1986 to 2007. The principal hydrochemical facies is calcium-bicarbonate (figs. 4*B* and 5) in the Río Jacaguas to the Río Descalabrado area.

The Río Descalabrado to the Río Jueyes

Historical data from well 16 indicated a change from sodium-bicarbonate to sodium-chloride water type (fig. 4*C*) and an increase of 586 mg/L in dissolved solids concentration from 1986 to 2007 (Gómez-Gómez, 1991). This increase was probably caused by the upconing of groundwater from deeper parts of the aquifer. The historic trend of chemical characteristics in well 28 indicates a decrease of 144 mg/L in dissolved solids concentration and a change from calcium-bicarbonate to calcium-chloride water type from 1986 to 2007 (fig. 4*C*). Analytical results from well 19 indicated a trend of potential change from calcium-bicarbonate to calcium-chloride water type (figs. 4*C* and 5). The principal hydrochemical facies in this area is calcium-bicarbonate based on analytical results from the wells east of Río Coamo. These results indicate that the aquifer is affected by this stream (figs. 4*C* and 5). Sodium-chloride water type is present in well 16, which is located near an outcrop of the Ponce Limestone and the Juana Díaz Formation. The Juana Díaz Formation can contain evaporates and other residues of marine origin (Giusti, 1971), thus causing the chemical characteristics measured in well 16. Well 17 plots on the boundary between calcium-bicarbonate and calcium-chloride water types. The calcium-chloride water type was present in wells 23, 28, and 29.

The Río Jueyes to the Río Seco

Dissolved solids concentrations in this area ranged from 492 to 19,900 mg/L (fig. 3). Wells 37 (936 mg/L), 38 (4,260 mg/L), and 39 (19,900 mg/L) were drilled to 50, 115, and 225 feet, respectively (table 1). These results are evidence of the mixing of freshwater and saline water related to depth in the aquifer. Dissolved solids concentrations increased in wells 43 (270 mg/L), 51 (70 mg/L), 52 (151 mg/L), and 53 (130 mg/L) from 1986 to 2007 (Gómez-Gómez, 1991). The area where these wells are located is classified as having the potential of changing its water type from calcium-bicarbonate to calcium-chloride or sodium-chloride (fig. 5). The dissolved solids 800-contour-line delineated inland near wells 43 and 49 coincides with a buried bedrock-high inferred by Renken and others (2002). In the Río Jueyes to the Río Seco area, the principal water type is calcium-bicarbonate (figs. 4*D* and 5). Calcium-chloride water type was detected in wells 37, 38, 45, and 49 located near the coastline in the Salinas area (fig. 5). Well 39 is on the boundary between the calcium-chloride and sodium-chloride types and well 50 indicates a sodium-chloride water type. Well 54 showed sodium-bicarbonate water type that is associated with inter-fan areas. Lower dissolved solids concentrations distribution east of the Río Nigua indicates that the aquifer is affected by streamflow infiltration.

East of the Río Seco

Dissolved solids concentrations in this area ranged from 267 to 744 mg/L (fig. 3). Dissolved solids concentration in well 55 increased from 320 to 393 mg/L from 1986 to 2007. The principal water type in this area is the calcium-bicarbonate (figs. 4*E* and 5). Well 56 plots on the boundary of calcium-sodium bicarbonate type water (fig. 4*E*).

Chloride-to-Bromide Ratio in Groundwater

Figure 6 shows the chloride-to-bromide ratio on a mole per mole basis in relation to chloride showing the theoretical freshwater-saltwater mixing line. The molar chloride-to-bromide ratio of seawater is approximately 640, based on chloride and bromide concentrations of 19,000 and 67 mg/L, respectively (Hem, 1989), which is similar to low chloride freshwater from wells located near the streams flowing through the coastal plain. Groundwater mixing between these endpoint sources will yield a proportional value to each that plots along the freshwater-seawater mixing line (Land and others, 2004). Groundwater with higher chloride concentration (above 250 mg/L) from wells 2, 3, 5, 23, 26, 28, 29, 37 to 39, 45, 49, and 50 reflects the mixing with seawater. Wells 16 to 19 and 24 in the Santa Isabel area and wells 44 and 45 in the Salinas area showed a low chloride-to-bromide ratio (less than 300) indicative of bromide enrichment relative to chloride. Bromide enrichment is associated with brine sources (Morell and others, 1986) and the use of pesticides and their application to agricultural fields (Flury and Papritz, 1993; Vengosh and Pankatov, 1998; Custodio and Alcalá-García, 2003).

Classification of Groundwater Quality

Groundwater samples collected from irrigation wells were classified (fig.7) using the U.S. Department of Agriculture (USDA) irrigation water classification diagram (Richards, 1954). Water is classified as being a low, medium, high, or extremely high sodium and salinity hazard, using the sodium adsorption ratio (SAR) and the specific conductance. Most of the samples from wells used for irrigation were in the classification of low sodium hazard and medium to high salinity hazard. High salinity hazard water can be used for irrigation only in soils with moderate to good permeability. Wells 2, 3, and 29 were classified as very high salinity hazard water. Water in this classification is generally undesirable for irrigation and is only suitable for occasional use on soils of good or high permeability (Richards, 1954). During the sample collection period, users of groundwater from well 29 attributed the adverse effects to their crops on the quality of the irrigation water.

All groundwater samples were classified into four categories based on the dissolved solids concentrations and the specific conductance: fresh, slightly saline, moderately saline, and very saline (fig. 8; Robinove and others, 1958; Díaz, 1974). All samples from public-supply, domestic, and industrial wells were in the freshwater category. Seven samples from public-supply wells had dissolved solids concentrations above 500 mg/L, which is the drinking-water secondary maximum contaminant level (SMCL) for dissolved solids (U.S. Environmental Protection Agency, 2003). Most samples from irrigation wells were classified as freshwater; however, four wells plotted in the slightly saline category (wells 2, 3, 16, and 29). Samples from piezometers near the coast in Santa Isabel and Salinas (wells 38, 39, 45, 49, and 50) were in the slightly (wells 45 and 50), moderately saline (26, 38, and 49), and very saline (well 39) water categories.

Conclusions

A synoptic groundwater-quality survey was conducted by the U.S. Geological Survey in the South Coast aquifer from Ponce to Arroyo in south-central Puerto Rico from April 2 through May 30, 2007. The data obtained consisted of in-situ measurements at active wells or piezometers for physical properties and water sample collection for laboratory analyses of common dissolved constituents and trace constituents. A total of 61 water samples were collected. These data were used to define the regional distribution of dissolved solids concentration and major hydrochemical facies in the aquifer system. Dissolved solids concentrations ranged from 324 to about 19,900 mg/L. In general, dissolved solids concentrations below 500 mg/L were detected near streams and concentrations above 800 mg/L matched with areas of potential mixing of freshwater and seawater. The principal hydrochemical facies in the study area is calcium-bicarbonate, which is associated with the freshwater infiltration through soils and surficial deposits. Calcium-chloride water type, which is associated with the mixture of saline and freshwater, has been detected in the Ponce, Santa Isabel, and Salinas areas. Analyses of samples collected at a well in the Ponce area indicate that the water is a sodium-chloride type associated with the intrusion of saline water. Sodium-bicarbonate water, which is associated with the weathering of minerals present in volcanic rocks, was detected in the inter-alluvial-fan areas near Santa Isabel and Salinas. Hydrochemical facies delineated in this survey are similar to those defined by a USGS study conducted in 1986. Compared to the 1986 conditions, changes were observed in the Ponce and Santa Isabel area, where sodium-chloride and calcium-chloride facies were detected, respectively. The chloride-to-bromide ratio in groundwater samples is evidence that mixing of freshwater and seawater is occurring in areas near the coast in Ponce, Santa Isabel, and Salinas. Some wells in the Santa Isabel and Salinas areas showed a low chloride-to-bromide ratio, which is indicative of bromide enrichment relative to chloride.

Samples from irrigation wells were classified into categories of low to high sodium hazard and categories of medium to very high salinity hazard using the USDA irrigation water classification. Collected samples were classified based on the dissolved solids concentrations; all samples from public-supply, domestic, and industrial wells were in the freshwater classification. Samples collected from USGS piezometers were classified in the fresh, slightly saline, moderately saline, and very saline water categories.

Initiating a salinity monitoring program would help resource managers evaluate further increases in dissolved solids concentrations near the coast of Ponce, Santa Isabel, and Salinas. A monitoring program could include existing piezometers and new piezometers drilled in areas where potential mixing of fresh and seawater was detected. Periodic sampling of the piezometers for dissolved solids could be used to determine the existence of any increased trends.

Base flow needs to be maintained in streams that traverse the coastal plain because of the effect that base flow has in maintaining low dissolved solids concentrations in the aquifer. Reduction of base flow resulting from surface-water diversions from these streams could contribute to the encroachment of saline water in the aquifer. The relation of surface water and groundwater needs to be evaluated to determine the amount of recharge to the aquifer from these streams.

References Cited

Bawiec, Walter, 2001, Geology, geochemistry, geophysics, mineral occurrences, and mineral resources assessment for the Commonwealth of Puerto Rico: U.S. Geological Survey Open-File Report 98-38.

Custodio, Emilio, and Alcalá-García, Francisco, 2003, El potencial de la relación Cl/Br como indicador del origen de la salinidad de los acuíferos costeros españoles: Tecnología de la intrusión de mar en acuíferos costeros, Instituto Geológico y Minero de España, p. 401-412.

Davis, S.N., Whittemore, D.O., and Fabrika-Martin, J., 1998, Uses of chloride/bromide ratios in studies of potable water: Ground Water, 36, no. 2: 338-350.

Díaz, J.R., 1974, Coastal salinity reconnaissance and monitoring system--south coast of Puerto Rico: U.S. Geological Survey Open-File Report 74-1, 28 p.

Flury, M., and Papritz, A., 1993, Bromide in the natural environment: Occurrence and toxicity: Journal of Environmental Quality, 22, p. 747-758.

Giusti, E.V., 1971, Water resources of the Coamo area, Puerto Rico: U.S. Geological Survey Water-Resources Bulletin 9, 31 p.

Glover, Lynn, 1971, Geology of the Coamo area, Puerto Rico, and its relation to the volcanic arc-trench association: U.S. Geological Survey Professional Paper 636, 102 p., 4 pls.

Hem, J.D., 1989, Study and interpretation of chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Land, M., Reichard, E.G., Crawford, S.M., Everett, R.R., Newhouse, M.W., and Williams, C.F., 2004, Ground-water quality of coastal aquifer systems in the West Coast Basin, Los Angeles County, California, 1999-2002: U.S. Geological Survey Scientific Investigations Report 2004-5067, 80 p.

Morell, I., Medina, J., Pulido, A., and Fernadez-Rubio, R., 1986, The use of bromide and strontium as indicator of marine intrusion in the aquifer of Oropesa-Torreblanca, in Boekelman, R.H. and others, eds., Proceedings 9th Saltwater Intrusion Meeting (SWIM), Water Management Group, Department of Civil Engineering: The Netherlands, Delf University of Technology, p. 629-640.

Panno, S.V., Hackley, K.C., Hwang, H.H., Greenberg, S.E., Kaprac, I.G, Landberger, S., and O'Kelly, D.J., 2006, Characterization and identification of Na-Cl sources in ground water: Ground Water, 44, no. 2: 176-187.

Piper, A.M., 1944, A graphic procedure in the geochemical interpretation of water analyses: American Geophysical Union Transactions, v. 25, p. 914-923.

Gómez-Gómez, Fernando, 1991, Hydrochemistry of the South Coastal Plain Aquifer system of Puerto Rico and its relation to surface water recharge, in Gómez-Gómez, Fernando, Quiñones- Aponte, Vicente, and Johnson, A.I., eds., Regional Aquifer Systems of the United States: Aquifers of the Caribbean Islands: American Water Association Monograph Series No. 15, International Symposium on Tropical Hydrology, July 1990, San Juan, Puerto Rico, p. 57-75.

Renken, R.A., Ward, W.C., Gill, I.P, Gómez-Gómez, Fernando, Rodríguez-Martínez, Jesús, and others, 2002, Geology and hydrogeology of the Caribbean Islands Aquifer System of the Commonwealth of Puerto Rico and the U.S. Virgin Islands: U.S. Geological Survey Professional Paper 1419, 139 p., 5 pls.

Richards, L.A., ed., 1954, Diagnosis and improvement of saline and alkali soils: Washington, D.C., U.S. Department of Agriculture Agricultural Handbook No. 60, 160 p.

Robinove, C.J., Langford, R.H., and Brookhart, J.W., 1958, Saline-water resources of North Dakota: U.S. Geological Survey Water-Supply Paper 1428, 72 p.

Rodríguez-Martínez, Jesús, Santiago-Rivera, Luis, Rodríguez, J.M., and Gómez-Gómez, Fernando, 2005, Surface-water, water-quality, and ground-water assessment of the municipio of Ponce, Puerto Rico, 2002-2004: U.S. Geological Survey Scientific Investigations Report 2005-5243, 96 p., 2 pls.

U.S. Environmental Protection Agency, 2003, National Secondary Drinking Water Standards: Office of Water, EPA 816-F-03-016.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1-A9.

Vengosh, A., and Pankatov, I., 1998, Chloride/bromide and chloride/fluoride ratios of domestic sewage effluents and associated contaminated ground water: Ground Water, 36, no. 5: 815-824.

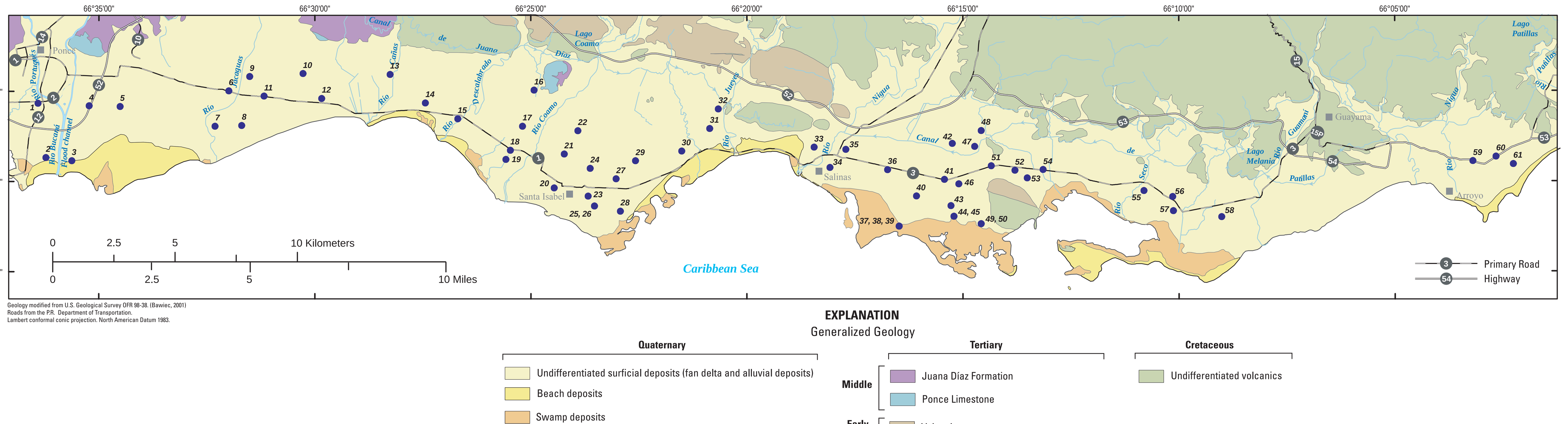

Figure 2. Sampled well locations and generalized geology in the Ponce to Arroyo area, Puerto Rico.

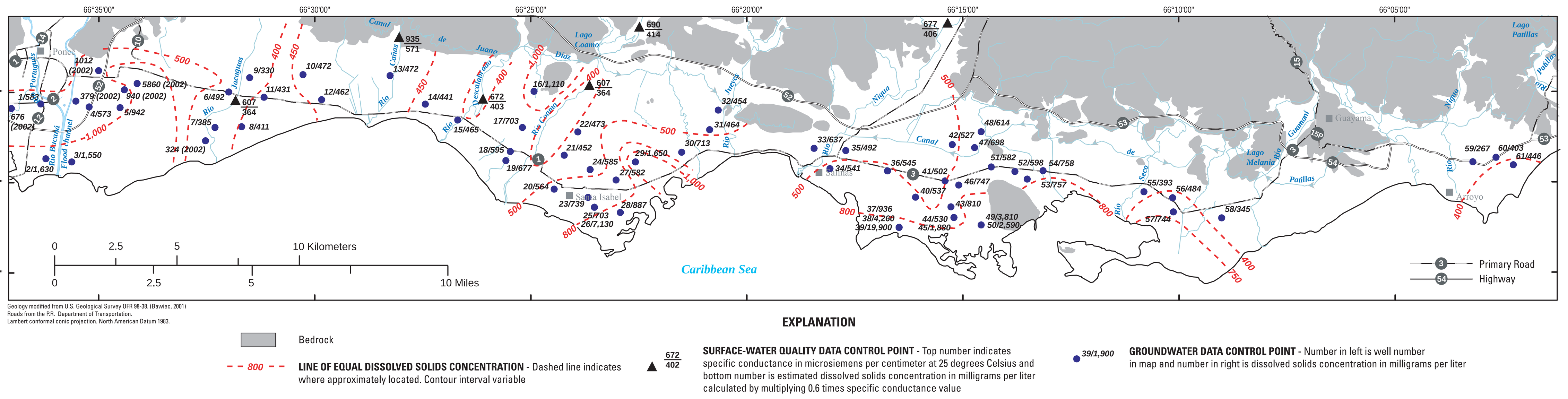

Figure 3. Dissolved solids distribution in the South Coast aquifer, April 2 through May 30, 2007.

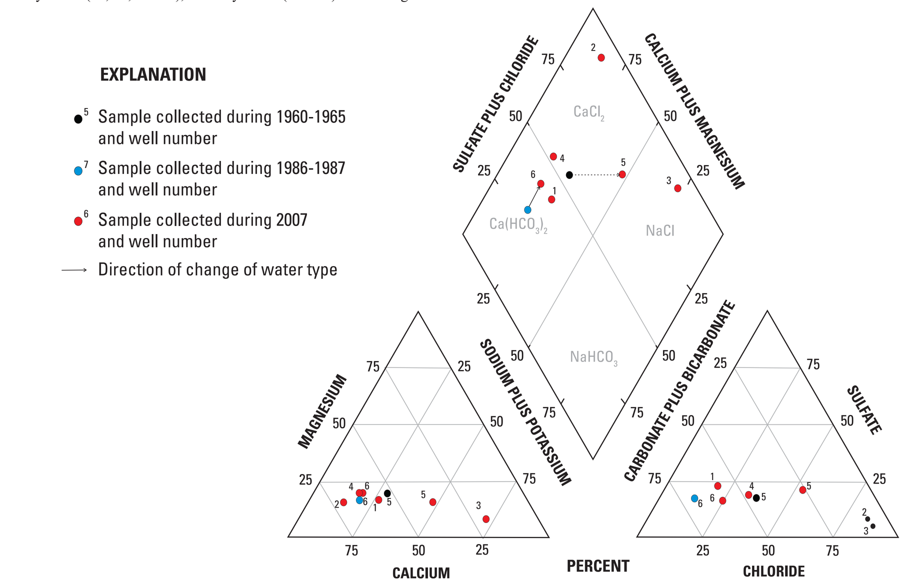

Figure 4A. Piper diagram showing main groundwater constituents and historical data in the area west of the Río Jacaguas, Puerto Rico.

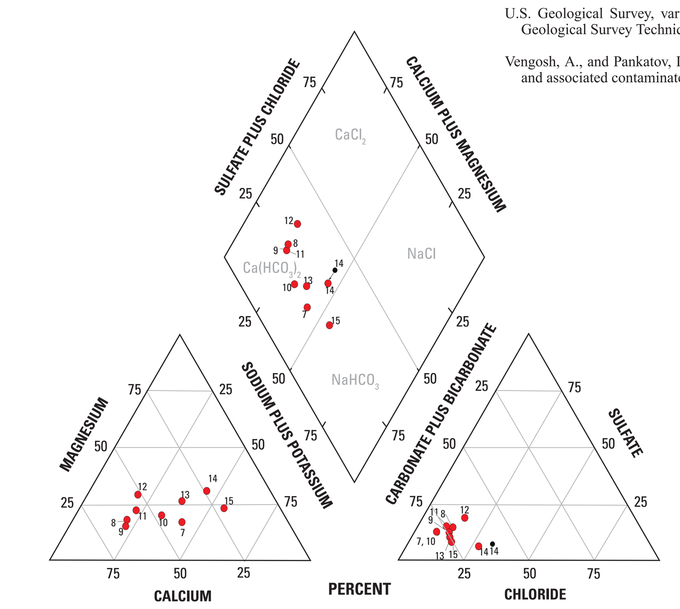

Figure 4B. Piper diagram showing main groundwater constituents and historical data in the Río Jacaguas to the Río Descalabrado area, Puerto Rico.

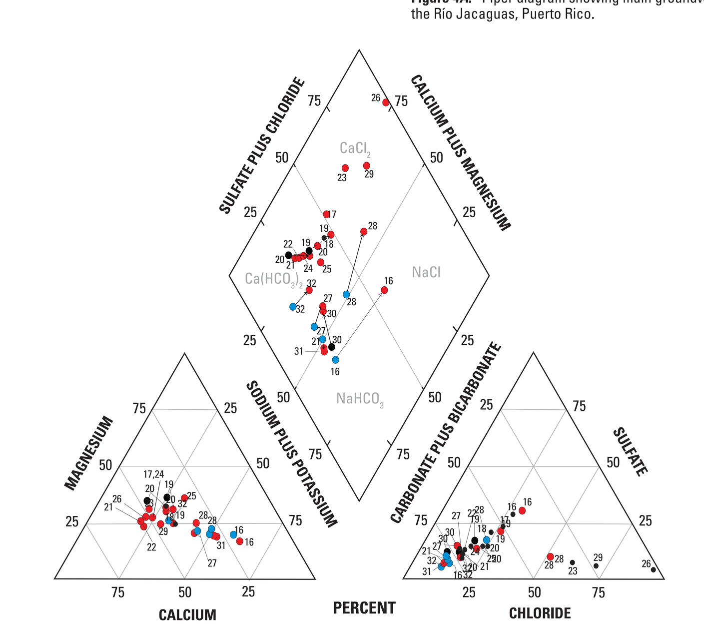

Figure 4C. Piper diagram showing main groundwater constituents and historical data in the Río Descalabrado to the Río Jueyes area, Puerto Rico.

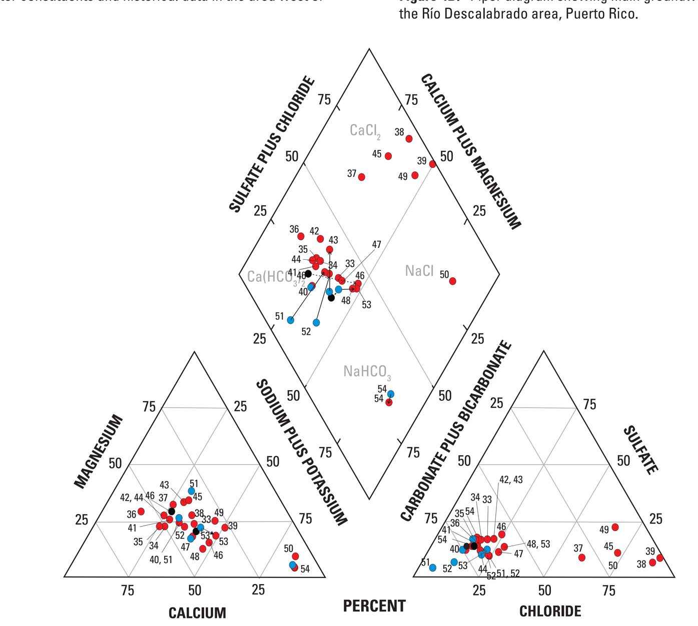

Figure 4D. Piper diagram showing main groundwater constituents and historical data in the Río Jueyes to the Río Seco area, Puerto Rico.

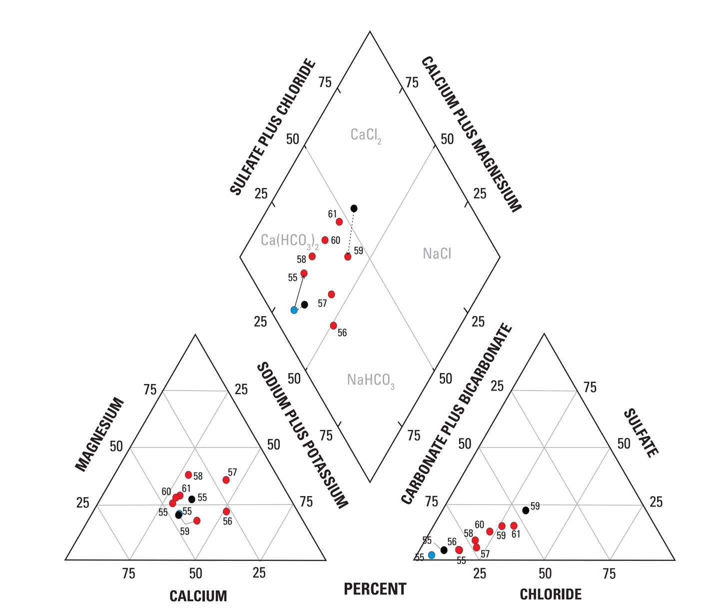

Figure 4E. Piper diagram showing main groundwater constituents and historical data east of the Río Seco area, Puerto Rico.

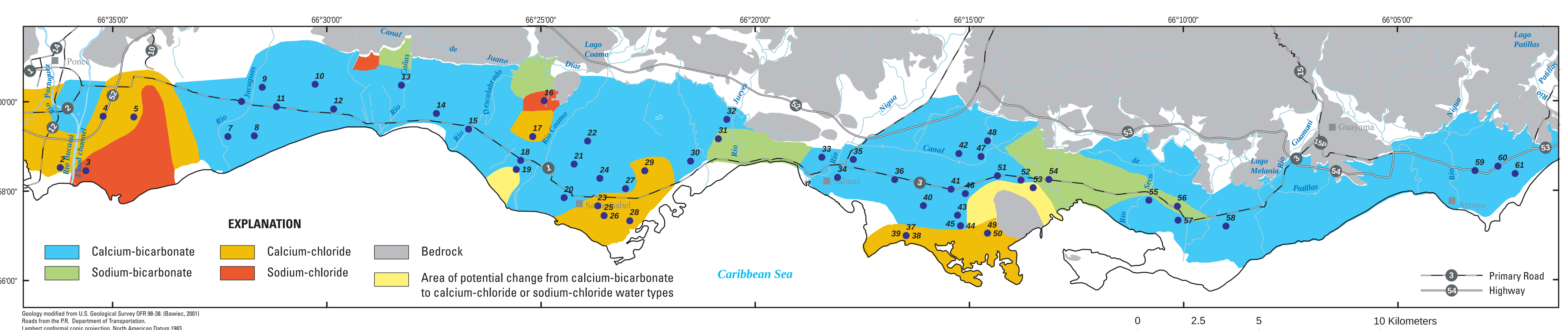

Figure 5. Hydrochemical facies in the South Coast aquifer, April 2 through May 30, 2007.

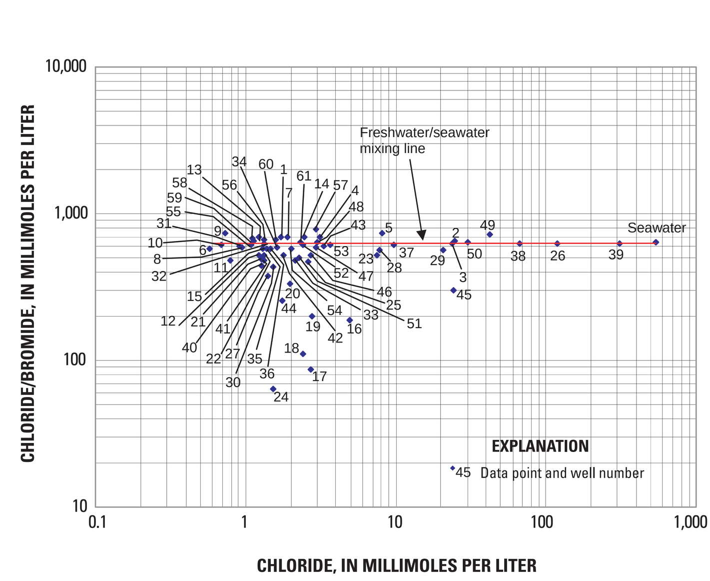

Figure 6. Chloride-to-bromide ratio as a function of chloride in groundwater from wells in the South Coast aquifer, April 2 through May 30, 2007.

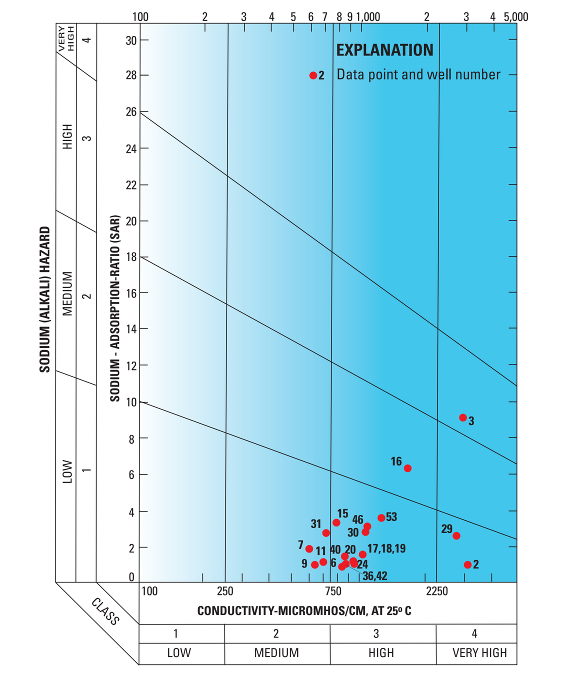

Figure 7. Classification of the groundwater collected from irrigation wells in the South Coast aquifer, April 2 through May 30, 2007 (irrigation water classification diagram modified from Richards, 1954).

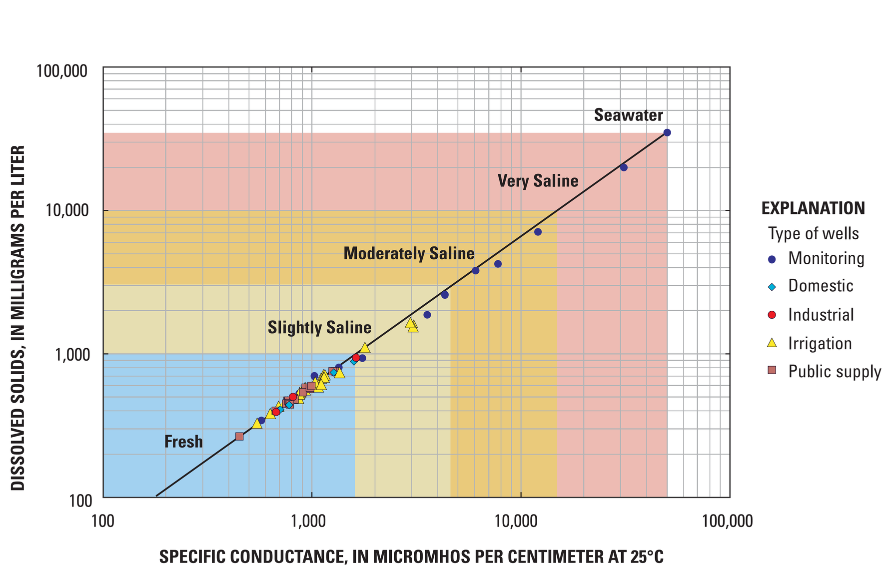

Figure 8. Classification of groundwater using dissolved solids concentration in samples from wells in the South Coast aquifer, April 2 through May 30, 2007.

Table 1. Physical and chemical characteristics in groundwater samples collected from selected wells in the Ponce to Arroyo area, Puerto Rico.

[NAD83, North American Datum 1983; concentrations are given in milligrams per liter, unless otherwise noted; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; $CaCO_3$; Calcium Carbonate; HCO_3, Bicarbonate; Ca, Calcium; Mg, Magnesium; K, Potassium; Na, Sodium; Cl, Chloride; F, Fluoride; SiO_2, Silica; SO_4, Sulfate; B, Boron; Fe, Iron; Br, Bromide; <, less than the analytical detection limit; na, data not available] [Map number refers to well locations shown on figure 2]

										Dissolved constituents														
Map number (fig.2)	USGS site identification	Latitude Longitude (NAD83)	Date of sample collection	Depth of well (feet)	pH	Specific conductance (µS/cm)	Temperature (Degrees C)	Acid neutralization capacity, (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Ca	Mg	K	Na	Cl	F	SiO_2	SO_4	B (µg/L)	Fe (µg/L)	Mn (µg/L)	Br	Dissolved solids, sum of constituents	Cl/Br (molar basis)	Sodium adsorption rate (SAR)
1	175952066362200	175945 663621	4/30/2007	na	7.0	960	28.6	283	345	115	21.9	1.01	57.0	61.5	0.13	37.3	110	90.8	<6	1.1	0.20	583	693	na
2	175839066361500	175832 663614	5/30/2007	na	7.4	3,070	30.2	116	141	404	57.5	2.87	77.9	879	<0.10	27.7	106	27.6	<6	0.8	3.07	1,630	645	1.0
3	175835066353900	175828 663538	5/30/2007	192	7.7	3,040	27.3	107	130	104	26.5	21	398	847	0.11	30.3	57.3	76.7	18	2.7	3.02	1,550	632	9.0
4	175948066351500	175941 663514	4/19/2007	na	6.9	980	28.1	236	288	126	25.1	0.67	36.1	110	0.10	34.5	94.5	51.2	<6	<0.2	0.36	573	689	na
5	175947066343200	175940 663431	4/30/2007	256	7.2	1,620	27.2	211	257	115	31.6	1.72	164	289	0.16	38.2	170	79.2	7	0.8	0.89	942	732	na
6	180009066320100	180001 663200	4/19/2007	na	7.1	864	28	244	297	110	22.5	0.88	35.3	67.7	0.12	33.9	68.4	52.2	<6	0.2	0.22	492	694	0.8
7	175921066322000	175914 663219	4/19/2007	64	7.1	632	27.8	253	308	54.0	14.2	0.82	65.4	20.5	0.21	34.0	38.3	89.4	<6	0.9	0.08	385	578	2.0
8	175923066314300	175915 663142	5/2/2007	120	7.3	706	29.1	249	303	87.8	15.5	1.14	34.9	33.9	0.15	35.5	48.7	67.7	25	3.1	0.13	411	588	na
9	180027066313200	180020 663131	4/19/2007	148	7.2	546	28	199	242	70.7	10.9	1.21	26.9	26.0	0.11	28.4	33.2	51	<6	<0.2	0.08	330	732	0.8
10	180031066301800	180024 663017	5/2/2007	165	7.2	764	28.3	318	387	76.3	20.3	0.72	62.4	24.6	0.16	39.6	50.8	171	15	<0.2	0.09	472	616	na
11	180001066311200	175954 663111	4/17/2007	na	7.2	693	27.8	253	308	83.1	20.2	1.26	36.8	27.8	0.12	34.3	49.6	71.4	<6	0.5	0.13	431	482	0.9
12	175958066295200	175951 662951	4/18/2007	na	7.3	765	27.7	251	306	82.2	28.9	0.8	37.9	43.8	0.20	37.3	74.8	56.4	<6	3.7	0.19	462	520	na
13	180029066281700	180023 662816	4/17/2007	na	6.8	772	27.7	291	355	61.3	26.8	0.7	73.0	43.2	0.43	35.8	38.1	210	<6	<0.2	0.14	472	695	na
14	175952066272800	175945 662727	4/13/2007	na	7.7	778	26.5	227	275	38.0	29.2	0.41	81.3	86.8	0.33	38.5	26.7	156	<6	<0.2	0.28	441	699	na
15	175931066264300	175924 662642	4/13/2007	na	7.6	765	27.5	287	349	34.2	22.6	0.98	103	45.8	0.24	32.4	34.9	198	<6	<0.2	0.18	465	573	3.4
16	180007066245500	180002 662456	4/13/2007	na	7.3	1,740	28.2	383	466	72.8	38.1	2.12	260	174	0.65	39.8	239	560	<6	<0.2	2.08	1,110	189	6.1
17	175921066252700	175914 662512	4/11/2007	na	7.2	1,130	27.5	247	301	108	38.5	1.04	60.1	95.6	0.18	38.4	112	143	<6	<0.2	2.49	703	87	1.3
18	175848066253100	175842 662529	4/11/2007	na	7.1	1,070	27.5	273	333	90.7	39.9	0.78	71.0	85.0	0.15	39.8	97.3	169	<6	<0.2	1.72	595	111	1.6
19	175839066253900	175830 662535	4/11/2007	160	7.0	1,100	27.5	271	330	86.6	41.8	0.91	76.3	98.7	0.16	39.8	109	176	<6	<0.2	1.12	677	199	1.7
20	175758066242700	175752 662428	4/12/2007	193	7.0	929	27.8	289	352	78.6	37.5	1.14	59.2	69.4	0.18	42.2	58.1	136	<6	0.6	0.47	564	333	1.4
21	175844066241500	175837 662414	4/5/2007	na	7.1	753	27.5	263	320	82.1	24.4	1.01	37.3	45.6	0.16	36.6	39.6	87.1	<6	<0.2	0.21	452	489	na
22	175916066235600	175908 662355	4/11/2007	na	7.2	770	27.8	263	320	87.1	24.1	1.6	41.3	46.7	0.12	36.5	48.7	103	<6	<0.2	0.20	473	526	na
23	175748066234200	175741 662341	4/18/2007	na	7.2	1,360	27.7	193	235	124	48.7	0.89	62.3	266	0.15	41.3	42.0	115	6	4.1	1.15	739	521	na
24	175825066233900	175818 662338	4/11/2007	216	7.2	928	27.5	273	333	93.4	32.6	0.84	52.5	54.5	0.20	41.4	55.8	137	<6	<0.2	1.93	585	64	1.2
25	175734066233300	175728 662332	5/18/2007	70	7.1	1,020	28.8	349	425	79.7	55.2	7.61	87.3	93.0	0.26	40.7	80.1	197	402	187	0.45	703	466	na
26	175734066233301	175728 662332	5/18/2007	250	7.1	12,000	28.1	101	123	1310	430	10	622	4,220	0.10	26.4	257	231	1,930	1,500	15.1	7,130	630	na
27	1758090662302	175804 662302	4/5/2007	na	7.0	933	27.6	329	401	70.1	25.5	0.96	96.5	50.4	0.19	44.6	61.8	225	<6	<0.2	0.30	582	379	na
28	175728066225800	175721 662256	4/18/2007	40	7.4	1,580	29.4	295	356	103	48.4	1.49	153	276	0.15	48.3	73.3	325	<6	0.4	1.11	887	560	na
29	175835066223600	175828 662235	4/12/2007	na	7.0	2,950	27.7	333	406	270	88.4	2.29	187	730	0.14	41.1	85.3	340	<6	<0.2	2.91	1,650	565	2.5
30	175848066213300	175841 662131	4/12/2007	na	7.1	1,140	27.1	419	510	88.4	27.7	1.61	120	54.1	0.15	42.9	87.2	429	<6	<0.2	0.28	713	435	2.9
31	175917066205400	175911 662052	4/12/2007	157	7.2	741	27.6	301	367	44.7	18.8	0.67	97.3	32.0	0.53	40.1	29.4	243	<6	<0.2	0.12	464	601	3.1

Table 1. Physical and chemical characteristics in groundwater samples collected from selected wells in the Ponce to Arroyo area, Puerto Rico—Continued

[NAD83, North American Datum 1983; concentrations are given in milligrams per liter, unless otherwise noted; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; $CaCO_3$; Calcium Carbonate; HCO_3, Bicarbonate; Ca, Calcium; Mg, Magnesium; K, Potassium; Na, Sodium; Cl, Chloride; F, Fluoride; SiO_2, Silica; SO_4, Sulfate; B, Boron; Fe, Iron; Br, Bromide; <, less than the analytical detection limit; na, data not available] [Map number refers to well locations shown on figure 2]

										Dissolved constituents														
Map number (fig.2)	USGS site identification	Latitude Longitude (NAD83)	Date of sample collection	Depth of well (feet)	pH	Specific conductance (µS/cm)	Temperature (Degrees C)	Acid neutralization capacity, (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Ca	Mg	K	Na	Cl	F	SiO_2	SO_4	B (µg/L)	Fe (µg/L)	Mn (µg/L)	Br	Dissolved solids, sum of constituents	Cl/Br (molar basis)	Sodium adsorption rate (SAR)
32	175944066204200	175937 662040	4/12/2007	na	7.1	777	28.2	279	340	66.7	24.8	0.97	62.4	47.5	0.43	37.4	39.2	179	<6	<0.2	0.17	454	630	na
33	175853066182800	175846 661827	4/18/2007	na	7.1	1,040	28.3	317	386	83.6	30.7	1.55	95.4	75.2	0.42	36.8	83.0	276	<6	0.5	0.35	637	484	na
34	175826066180600	175819 661805	4/4/2007	na	7.0	906	29	303	369	94.3	26.2	1.07	59.8	57.5	0.31	39.3	73.9	184	<6	<0.2	0.22	541	589	na
35	175851066174600	175843 661743	4/4/2007	120	7.1	819	28.6	277	336	87.5	24.1	1.04	50.8	49.0	0.29	38.0	68.9	161	<6	<0.2	0.19	492	581	na
36	175823066164600	175816 661645	4/17/2007	na	6.9	884	27.7	293	357	91.9	28.6	1.37	57.6	51.7	0.33	38.4	65.8	153	<6	<0.2	0.20	545	583	1.3
37	175708066163001	175701 661629	5/22/2007	50	7.0	1,740	27.2	254	310	141	65.7	2.32	102	345	0.22	41.8	65.9	184	156	21.3	1.27	936	612	na
38	175708066163000	175701 661629	5/22/2007	115	6.7	7,740	27.7	203	248	578	251	4.75	609	2,390	0.30	38.8	246	178	6	0.41	8.53	4,260	631	na
39	175708066163002	175701 661629	5/22/2007	220	6.6	31,000	28.2	179	218	1,970	988	15.4	4,180	11,000	0.12	30.6	1,520	392	103	25.1	39.9	19,900	621	na
40	175748066160400	175741 661605	4/4/2007	162	7.3	874	27.4	315	384	79.7	26.9	0.93	68.2	45.3	0.38	40.7	50.8	177	<6	<0.2	0.23	537	444	1.7
41	175810066152700	175803 661526	4/18/2007	120	7.0	810	28	261	318	80.3	26.6	0.83	53.4	47.3	0.34	39.1	54.1	125	3	0.2	0.22	502	485	na
42	175858066151600	175851 661515	4/3/2007	na	7.1	869	28.3	251	306	85.3	28.8	0.96	48.8	62.9	0.28	37.7	71.6	109	<6	0.6	0.27	527	525	1.2
43	175735066151800	175728 661517	5/17/2007	82	7.0	1,340	27.5	431	525	110	58.4	0.5	98.3	117	0.39	39.7	118	227	<6	4.9	0.44	810	599	na
44	175721066151400	175714 661513	5/16/2007	87	7.2	870	27.3	297	362	90.8	31.2	1.06	54.8	61.9	0.29	39.2	51.5	121	16	<0.2	0.24	530	258	na
45	175721066151401	175714 661513	5/16/2007	20	7.0	3,560	27.5	275	335	216	126	1.12	222	852	0.97	37.0	169	375	<6	694	2.86	1,880	298	na
46	175804066150700	175757 661506	4/4/2007	150	7.1	1,150	27.8	309	377	85.4	22.8	1.23	129	96.5	0.27	39.4	96.9	286	<6	<0.2	0.42	747	518	3.2
47	175854066144500	175847 661444	4/2/2007	na	7.1	1,140	28.8	341	416	96.2	25.3	0.96	106	105	0.48	38.9	59.5	264	<6	0.2	0.40	698	592	na
48	175916066144000	175908 661435	4/2/2007	300	6.9	1,110	27.6	311	379	88.2	16.9	1.07	117	107	0.63	33.5	63.4	314	<6	1.7	0.38	614	635	na
49	175711066143600	175704 661435	5/16/2007	74	6.8	6,060	28.1	379	462	409	195	2.5	700	1,510	0.47	39.2	699	838	<6	18.2	4.76	3,810	715	na
50	175711066143601	175704 661435	5/17/2007	17	7.5	4,320	28.5	419	509	63.8	43.0	6.24	794	1070	0.42	38.2	158	566	8.4	242	3.75	2,590	643	na
51	175828066142200	175821 661421	4/2/2007	na	7.0	977	28.4	309	377	85.0	30.2	0.97	74.1	80.5	0.32	38.4	44.7	192	<6	<0.2	0.36	582	504	na
52	175822066134800	175815 661348	4/2/2007	118	7.1	993	27.9	315	384	89.0	27.9	1.11	84.0	86.3	0.34	38.4	45.2	219	<6	<0.2	0.32	598	608	na
53	175812066133200	175805 661331	4/18/2007	150	7.1	1,290	27.8	379	462	86.3	30.3	1.08	148	130	0.43	38.8	84.8	395	8	0.2	0.48	757	610	3.5
54	175824066130900	175816 661309	4/4/2007	na	7.5	1,250	29.3	451	548	23.6	7.5	0.51	246	71.5	1.81	35.8	87.5	711	16	0.3	0.28	758	576	na
55	175755066105000	175748 661049	4/3/2007	85	6.8	673	27.9	269	328	65.9	21.8	0.92	45.6	38.2	0.32	35.6	16.5	114	<6	<0.2	0.14	393	615	na
56	175747066101000	175740 661009	4/3/2007	na	6.8	825	27.7	336	410	47.8	22.0	0.75	98.7	46.9	0.60	36.1	23.0	203	<6	<0.2	0.16	484	661	na
57	175728066100900	175721 661008	5/2/2007	na	7.5	1,270	28.7	497	604	57.1	59.6	0.53	141	105	0.65	37.5	39.2	421	80	158	0.30	744	789	na
58	175719066085500	175713 660901	5/17/2007	99	7.3	572	27.8	205	250	48.3	21.8	0.31	44.7	39.4	0.51	39.1	24.5	116	<6	0.7	0.13	345	683	na
59	175832066031300	175827 660312	4/3/2007	120	6.3	449	28.2	123	150	36.0	9.6	0.54	42.0	40.2	0.27	30.9	30.7	99.2	<6	<0.2	0.14	267	647	na
60	175840066024100	175833 660240	4/3/2007	na	6.6	669	28.5	215	262	63.2	23.7	0.45	47.3	56.1	0.27	37.3	42.3	86.2	<6	0.3	0.19	403	665	na
61	175832066022000	175823 660216	4/3/2007	na	6.9	783	27.5	201	245	63.8	26.4	0.46	54.1	81.9	0.28	37.0	57.2	100	<6	<0.2	0.29	446	637	na

GROUNDWATER-QUALITY SURVEY OF THE SOUTH COAST AQUIFER OF PUERTO RICO, APRIL 2 THROUGH MAY 30, 2007

By José M. Rodríguez and Fernando Gómez-Gómez

2009

USGS
science for a changing world

U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Introduction

The increased potential for variability of groundwater quality in the South Coast aquifer of Puerto Rico due to saline water encroachment from the Caribbean Sea and from deep parts of the aquifer has become a major concern of water planners and managers. In an effort to determine the extent and sources of this encroachment, the U.S. Geological Survey (USGS) and the Puerto Rico Department of Natural and Environmental Resources conducted a synoptic groundwater-quality survey from April 2 through May 30, 2007, for the South Coast aquifer between Ponce and Arroyo (fig. 1). Groundwater resources in this aquifer extend 150 square miles in south-central Puerto Rico and provide an estimated 44.2 million gallons per day (Mgal/d) or about 61 percent of the total water needs. This amount includes: 15.3 Mgal/d for irrigation, 27.4 Mgal/d for public supply, and 1.5 Mgal/d for industrial and other uses (W.L. Molina-Rivera, U.S. Geological Survey, written commun., 2007). Since 1980 when most of the south coastal plain was intensively cultivated for sugarcane, total groundwater withdrawals have declined about 32 Mgal/d with the greatest decline occurring in irrigation (37.2 Mgal/d) and the greatest increase occurring in public supply (5.5 Mgal/d). Although withdrawals have declined substantially, a major concern is that aquifer recharge provided by irrigation return flow from surface-water irrigation canals has essentially dropped to zero because of the large-scale implementation of groundwater drip irrigation systems.

Purpose and Scope

The purpose of this report is to present the assessment of groundwater-quality data obtained during the synoptic survey conducted April 2 through May 30, 2007, that can be used by water-resource managers and planners to gain a better understanding of aquifer conditions. The data consist of in-situ measurements at active wells or piezometers for specific conductance, pH, temperature and acid neutralizing capacity (ANC, formerly referred to as alkalinity, ANC is now used exclusively for filtered water samples) and water sample collection and preparation for laboratory analyses of common dissolved constituents (ANC, calcium, magnesium, sodium, potassium, sulfate, fluoride, silica) and trace constituents (boron, iron, and manganese). These data were used to define the regional distribution of dissolved solids concentration and major hydrochemical facies in the aquifer. The data were also compared to historical data collected at several sites in the study area.

Hydrogeologic Setting

The survey area in Puerto Rico is between Ponce and Arroyo and is bound to the north by the foothills of the Cordillera Central and the Sierra de Cayey Mountains, to the south by the Caribbean Sea, to the west by the Río Portugués, and to the east by the Río Patillas (fig. 1 and 2). The major geologic units in the survey area are also presented on figure 2. Groundwater occurs primarily in Quaternary surficial deposits that include fan delta and alluvial sediments. These deposits are typically less than 100 feet thick in areas east of the Río Jueyes, but could be as much as 1,000 feet thick near the coast in areas to the west of the Río Jueyes (Renken and others, 2002). The surficial deposits between the Río Portugués at Ponce and the Río Coamo are underlain by carbonate units of Tertiary age with permeable limestone units that are hydraulically connected with the surficial deposits, thus both hydrogeologic units are considered as one aquifer unit in this area. The basal part of the aquifer in the Río Portugués to Río Coamo area consists of claystone strata of the underlying Juana Díaz Formation (fig. 2). Volcanic rocks of Tertiary and Cretaceous age form the base of the aquifer east of Santa Isabel.

Methods and Techniques

Groundwater samples were collected once from 50 active wells that include: 23 wells for irrigation use, 19 wells for public-supply use, 5 wells for industrial use, and 3 wells for domestic use. In addition, 11 piezometers were pumped using a 0.75 horsepower submersible pump to collect samples representative of groundwater at the respective well-screen interval open to the aquifer. Water samples were collected during April and May 2007, a period of stable hydrologic conditions at the end of the relatively dry season along the south coast. Field measurements were obtained and water samples for laboratory analyses were collected and preserved according to USGS protocols (U.S. Geological Survey, variously dated). Water samples were analyzed at the USGS National Water Quality Laboratory in Denver, Colorado. The analytical results were used to develop a map showing the distribution of dissolved solids in the aquifer consisting of the sum of the concentration of cations (calcium, magnesium, sodium, and potassium), anions (sulfate and fluoride), silica, and carbonate. Specific conductance measurements and their conversion to dissolved solids concentration values at selected surface-water sites are included in figure 3 to present the effects of streams on dissolved solids concentrations in the aquifer.

Hydrochemical facies were used to delineate aquifer areas as to the prevailing water type using the trilinear diagram method (Piper, 1944). Predominant end-member hydrochemical facies in the survey area are: sodium bicarbonate [$NaHCO_3$], sodium chloride [NaCl], calcium bicarbonate [$Ca(HCO_3)_2$], and calcium chloride [$CaCl_2$]. The $NaHCO_3$ results from the weathering of plagioclase minerals present in the volcanic rocks along the northern perimeter of most of the coastal plain and in areas where the volcanic rocks form the base of the aquifer. The NaCl results from seawater encroachment along the coast and $Ca(HCO_3)_2$ from freshwater infiltration through soils and surficial deposits. The $CaCl_2$ results from groundwater in the limestone rocks that lie along the perimeter of the aquifer or at depth, especially in the western half of the coastal plain. This residual sodium chloride in the rock matrix and from aquifer areas contains a mix of freshwater and seawater. Hydrochemical facies for inland parts of the survey area were delineated using water-quality information from USGS databases. Because the